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Chief, Publications Branch
Technology Utilization Division, Code UT
NASA Headquarters
Washington, D. C. 20546

Attention: Mr. Edward N. Case

Subject: Submittal of Final Manuscripts (Chapter 1, "Introduction", Chapter 11, "Developmental Methods", and Related Material) in Accordance with Article H (Page 5) and Article VI, Paragraph B, of Contract NASw-1873

Gentlemen:

In compliance with Article H and Article VI, paragraph B, of Contract NASw-1873, enclosed are ten (10) copies of each of the following final manuscripts items:

(1) Chapter 1, "Introduction"

(2) Chapter 11, "Developmental Methods"

(3) Cover Page, Acknowledgements, and Contents

As specified in Contract NASw-1873, one copy each of Items (1) through (3) is being submitted to the following:

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Washington, D. C. 20546

(2) Technical Reports Control Officer (Code US)
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Also, we are sending you under separate cover the original illustrations for Items (1) and (2) as well as the remaining copyright permission correspondence not previously submitted.

These submittals complete SwRI commitments specified in Contract NASw-1873. We have enjoyed conducting this very important Survey for NASA Headquarters and look forward to other future opportunities in the TUS area.

Yours very truly,

John R. Barton

John R. Barton, Director
Instrumentation Research

WAH:maa

cc: Headquarters Contracts Division
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I

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IV

NONDESTRUCTIVE EVALUATION

A SURVEY OF NASA CONTRIBUTIONS

C. GERALD GARDNER
Technical Editor

Prepared under contract for the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

by

SOUTHWEST RESEARCH INSTITUTE
San Antonio, Texas

FOREWARD

(To be prepared by NASA)

ACKNOWLEDGEMENTS

The primary credit for the technical content of this Survey must, of course, be accorded those scientists and engineers of the various NASA Centers and industrial contractors upon whose technical contributions the Survey is based. These workers are cited individually through the references at the end of each chapter.

This Survey was undertaken through the initiative of NASA's Technology Utilization Division. The program was monitored by Leonard A. Ault, Chief, Identification and Publication Division, and Edward N. Case, Special Assistant to the Director for Publications. Mr. Ault's and Mr. Case's interest, constructive suggestions, and timeliness in reviewing the manuscript have contributed materially to the quality of the document.

Liaison for interviews with technical personnel at the various NASA Centers, and also for subsequent review of the draft manuscript by Center personnel was courteously and competently provided by the Technology Utilization Officers and their assistants attached to each of the Centers. These were: at Ames Research Center: George G. Edwards and Horace Emerson; Electronics Research Center: Fred Hills; Flight Research Center: Clinton T. Johnson; Goddard Space Flight Center: Kenneth F. Jacobs and Helen Attick; Jet Propulsion Laboratory: Wallis M. Tener; Kennedy Space Center: James O. Harrell; Langley Research Center: John Samos and Paul Kurbjun; Lewis Research Center: S. F. Felder; Manned Spacecraft Center: John Wheeler; Marshall Space Flight Center: H. L. Martin; Wallops Station: Chris Floyd.

The various authors of the individual chapters of the Survey are due a word of thanks for their patience and cooperation with the Technical Editor in securing a resonable measure of uniformity of organization and style from chapter to chapter.

Finally, a special acknowledgement is due William A. Hewgley, who managed the Southwest Research Institute project under which the Survey was prepared. Without his continuous guidance, perserverance, skillful direction of the project team, and unfailing support of the Technical Editor, this Survey would have been considerably diminished.

C. Gerald Gardner
San Antonio, Texas
1971

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Chapter 10	STRAIN SENSING	Robert R. King Felix N. Kusenberger	
Chapter 11	DEVELOPMENTAL METHODS	C. Gerald Gardner	

CHAPTER 1

INTRODUCTION

20 October 1971

Final Manuscript Submitted in Accordance
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for

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INTRODUCTION

Man has always been concerned with the quality and reliability of the things he fashions for himself, the products of his technology. Moreover, he has continually sought to improve upon his immediate senses as instruments by which to test these products. Archimedes' jubilant "eureka" was evoked not primarily because he had discovered the principle of flotation, but rather because that discovery afforded him a means of determining whether his king's newly made gold crown had been unduly alloyed with silver. In this respect, the most gifted technologist of antiquity was concerned with what today is called nondestructive evaluation (NDE).

While man's concern with nondestructive evaluation has always been manifest, his skills and implements for this task have generally lagged behind his technology as a whole. Indeed, most of the NDE methods in current practice were developed largely within the past half century; some are less than a decade old. Moreover, until quite recently, NDE was commonly regarded as a production shop activity, a mixture of craft and lore, the province of the skilled tradesman; rarely (as in the case of Archimedes) was it an area of concern for the engineer or scientist. As long as serviceability and safety could be secured by an engineering approach based on overdesign with large safety factors, such an unsophisticated approach to NDE was acceptable.

But with the advent of the modern technological era there has arisen the need for components and structures of unprecedented efficiency, the design of which demands of the constituent materials performance close to their ultimate capability. Such a design approach requires both a greatly improved understanding and exploitation of the engineering properties of classical materials, and the development and use of new materials including nonmetallics and composites. With these developments has come the need for commensurate improvements in the technology of nondestructive evaluation.

By the close of World War II, during which NDE surged forward in industrial usage, the "big five" NDE methods (liquid penetrant testing, magnetic particle testing, X-ray radiography, ultrasonic testing, and eddy current testing) had reached a mature, though not definitive, state of development. The post-war years brought with them the introduction of nuclear power plants, jet powered aircraft, the rocket powered ballistic missile, unmanned spacecraft, and finally manned spacecraft. These developments have exerted great influence on the further refinement of the "big five" NDE methods, as well as strain sensing and leak detection. The development of entirely new methods, including thermal and infrared testing, microwave testing, acoustic emission testing, and holographic testing, was also stimulated. Most of these refinements and new developments are founded upon advanced physics and electronics, and their development has required the efforts of highly trained scientists and engineers as well as skilled technicians.

The contemporary period in NDE development is characterized not only by the introduction of novel, sophisticated technical approaches, but also by a trend away from hand operations and toward substantially automated inspection systems. By greatly reducing the time required for inspection and by eliminating the uncertainties typically associated with "operator dependence" of hand operations, such automated systems are, in many cases, proving to be cost-effective despite their greater initial cost. Thus progress in systems engineering, electromechanical design, signal processing, information theory, computer technology, and cybernetics are increasingly prominent aspects of NDE development.

The aerospace industries and government agencies concerned with aerospace development play prominent roles in promoting the development and growth of NDE. Among these the National Aeronautics and Space Administration, through its several Centers and many of its contractors, is a significant contributor. NASA's contributions to NDE are, of course, by-products of its primary mission, the development of advanced aerospace vehicles and the exploration of the space environment. The extraordinary efficiency and reliability of modern aerospace structures has been achieved in no small measure because of the systematic, painstaking programs of reliability and quality assurance (R&QA) which have accompanied the development and production of these structures. In these R&QA programs, nondestructive evaluation plays a significant, though certainly not exclusive, role. NASA's influence on NDE technology is both indirect and direct -- indirect in the sense that NASA's needs have stimulated developments by their suppliers, and direct in the sense of explicit research and development efforts by both NASA Centers and contractors. Many NASA sponsored advances in NDE technology have potential applications outside the aerospace field. This Technology Utilization Survey is intended to serve primarily as a medium for the dissemination of these developments and for their transfer to non-aerospace applications.

Throughout industry, popular demand for a greater degree of quality, reliability, and safety in all products is currently focusing attention on NDE. The automotive and trucking industry, the railroad and high-speed ground transportation industry, the pipeline industry, and the ship building industry all stand to profit from advances in NDE technology. The electric utility industry, the construction industry, the home appliance industry, and the food industry likewise are recognizing that NDE, properly implemented, can more than pay for itself through improvements in product uniformity, fewer rejections, and reduced incidence of in-service failure.

Typically, the responsibility for recognizing the need for, and assessing the potential cost-benefit impact of, a new or revised NDE program in industry rests primarily at the level of middle management. For members of middle management with such responsibility, a general working knowledge of the available NDE methods and their capabilities and limitations has become a virtual necessity. It is to this audience that this Technology Utilization Survey is principally addressed. While this Survey is in no sense intended to be a textbook or treatise, it is hoped that it will serve the need of middle management for an overview of the field of NDE as a whole. Although a general technical faculty on the part of the reader has been supposed, no expert knowledge of nondestructive evaluation has been assumed.

The Survey is organized into chapters each of which deals with a major NDE method, with a concluding chapter on several methods still in the developmental stage. Each chapter contains a brief synopsis of the fundamental principles and practical procedures in standard use; the contributions made by NASA Centers and contractors are then presented against this background. These synopses are restricted in scope to the essentials required for a general understanding of the significance of the NASA contributions subsequently presented. In presenting the NASA contributions, emphasis has been placed upon basic principles and practical significance rather than upon technical details of implementation.

The primary documentation upon which this Survey is based consists of the pertinent NASA Technical Notes, Technical Memoranda, and Contractor Reports. This Survey is not intended as a substitute for the primary documentation, but as summary of it and guide to it. The primary documentation used in preparing this Survey is fully referenced, and readers who find a contribution of potential use to them should refer to the referenced document(s) for further, more detailed information.

Of the numerous NASA contributions described in this Survey, one in particular should be noted here. Recognizing that a successful NDE program depends crucially upon the knowledge and skill of practicing technicians, NASA has, through a contractor, prepared a series of instructional materials in each of the most widely used NDE methods (Refs. 1-18). For each method, the series provides a training handbook for use as a classroom text, together with one or more manuals of the so-called programmed type. These manuals are suitable for self-study, and are designed to lead the student step-by-step to a confident grasp of the principles, apparatus, and procedures of an NDE method. When used as part of a systematic training program led by competent instructors, and including a period of supervised apprenticeship, these materials provide the student with the knowledge and experience necessary for expert application of the method at the technician level. Now available through the American Society for Nondestructive Testing, these books may prove to be the NASA contribution most far reaching in its impact on the practice of NDE.

As an aid to the novice in NDE, Table I presents in brief outline the principal NDE methods discussed in this Survey. The Table

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TABLE I

COMPARISON OF SELECTED NDE METHODS

TUS Chapter	X-Ray Radiography 4	Neutron Radiography 4	Liquid Penetrants 2	Eddy Current Testing 5	Microwave Testing 7
Properties Sensed or Measured	Inhomogeneities in thickness, density, or composition	Compositional inhomogeneities; selectively sensitive to particular atomic nuclei	Material separations open to a surface	Anomalies in electric conductivity and, in cases, magnetic permeability	Anomalies in complex dielectric coefficient; surface anomalies in conductive materials
Typical Flaws Detected	Voids, pososity, inclusions, cracks	Presence, absence, or mislocation of internal components of suitable composition	Cracks, gouges, porosity, laps, seams	Cracks, seams, variations in alloy composition or heat treatment	In dielectrics: disbonds, voids, large cracks; in metal surfaces: surface cracks
Representative Application Areas	Castings, forgings, weldments, assemblies	Inspection of propellant or explosive charge inside closed ammunition or pyrotechnic devices	Castings, forgings, weldments, components subject to fatigue or stress-corrosion cracking	Wire, tubing, local regions of sheet metal, alloy sorting, thickness gauging	Glass fiber-resin structures; plastics; ceramics; moisture content; thickness measurement
Advantages	Detects internal flaws; useful on a wide variety of materials; portable; permanent record	Good penetration of most structural metals; high sensitivity to favorable materials; permanent record	Inexpensive; easy to apply; portable	Moderate cost; readily automated; portable; permanent record if needed	Non-contacting; readily automated; rapid inspection
Limitations	Cost; relative insensitivity to thin laminar flaws such as fatigue cracks and delaminations; health hazard	Cost; relative unportability; poor definition; health hazard	Flaw must be open to an accessible surface; messy; irrelevant indications often occur; operator dependent	Conductive materials only; shallow penetration; geometry sensitive; reference standards often necessary	No penetration of metals; comparatively poor definition of flaws

TUS Chapter	Magnetic Particles 8	Magnetic Field Testing 8	Ultrasonic Testing 3	Sonic Testing 3	Ultrasonic Holography 3
Properties Sensed or Measured	Anomalies in magnetic field flux at surface of part	Anomalies in magnetic field flux at surface of part	Anomalies in acoustic impedance	Anomalies in low-frequency acoustic impedance or natural modes of vibration	Same as ultrasonic testing
Typical Flaws Detected	Cracks, seams, laps, voids, porosity, inclusions	Cracks, seams, laps, voids, porosity, inclusions	Cracks, voids, porosity, delaminations	Disbonds, delaminations, larger cracks or voids in simple parts	Same as ultrasonic testing
Representative Application Areas	Castings, forgings, extrusions	Castings, forgings, extrusions	Castings, forgings, extrusions; thickness gauging	Laminated structures; honeycomb; small parts with characteristic "ring"	Inspection of small, geometrically regular parts
Advantages	Simple; inexpensive; senses shallow subsurface flaws as well as surface flaws	Good sensitivity to and discrimination of fatigue cracks; readily automated; moderate depth penetration; permenent record if needed	Excellent penetration; readily automated; good sensitivity and resolution; requires access to only one side; permanent record if needed	Comparatively simple to implement; readily automated; portable	Produces a viewable image of flaws
Limitations	Ferromagnetic materials only; messy; careful surface preparation required; irrelevant indications often occur; operator dependent	Ferromagnetic materials only; proper magnetization of part sometimes difficult	Requires mechanical coupling to surface; manual inspection is slow; reference standards usually required; operator dependent	Geometry sensitive; poor definition	Cost; limited to small parts; poor definition compared to radiography

TUS Chapter	Infrared Testing 6	Strain Gauges 10	Brittle Coatings 10	Optical Holography 11	Leak Detection 9
Properties Sensed or Measured	Surface temperature; anomalies in thermal conductivity and/or surface emissivity	Mechanical strains	Mechanical strains	Mechanical strains	Flow of a fluid
Typical Flaws Detected	Voids or disbonds in nonmetallics; location of hot or cold spots in thermally active assemblies	Not used for flaw detection	Not commonly used for flaw detection	Disbonds; delaminations; plastic deformation	Leaks in closed systems
Representative Application Areas	Laminated structures; honeycomb; electrical and electronic circuits	Stress-strain analysis of most materials	Stress-strain analysis of most materials	Honeycomb; composite structures; tires; precision parts such as bearing elements	Vacuum systems; gas and liquid storage vessels; pipage
Advantages	Produces a viewable thermal map	Low cost; reliable	Low cost; produces large area map of strain field	Extremely sensitive; produces map of strain field; permanent record if needed	Good sensitivity; wide range of instrumentation available
Limitations	Cost; difficult to control surface emissivity; poor definition	Insensitive to preexisting strains; small area coverage; requires bonding to surface	Insensitive to preexisting strains; messy; limited accuracy	Cost; complexity; requires considerable skill	Requires internal and external access to system; contaminents may interfere; can be costly

indicates for each method the basic property sensed or measured, some typical applications, and the most notable advantages and limitations of the method. Such a table (of which many similar versions are in circulation) is necessarily incomplete, and is intended to serve only the purpose of orientation. It should not be relied upon for making critical assessments of the potential application of a method to a specific NDE problem.

Finally, a word about terminology. Historically, the term "nondestructive testing" (NDT) has enjoyed widespread usage. Some have preferred the term "nondestructive inspection" (NDI). The _Ad Hoc_ Committee on Nondestructive Evaluation of the National Materials Advisory Board has stated that "the term nondestructive evaluation (NDE) is considered more appropriate ... since: (1) this discipline also requires the evaluation of test results and inspection; (2) the words 'testing and inspection' do not properly imply the theoretical aspects of this field; and (3) the name (nondestructive evaluation) is more succinct and descriptive." (Ref. 19) The recommendation of the NMAB _Ad Hoc_ Committee has been adopted for this Survey.

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CHAPTER 11

DEVELOPMENTAL METHODS

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Final Manuscript Submitted in Accordance
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Washington, D. C. 20546

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INTRODUCTION

This chapter includes brief accounts of three nondestructive evaluation (NDE) methods which have been introduced within the past few years. These are acoustic emission, the use of coherent (laser) light, and ultrasonic holography. The fact that these methods are already being put to use in a practical way, with commercial apparatus already available, is testimony to the rapid pace at which NDE is currently moving. While these methods have played no significant role in NASA reliability and quality assurance programs to date, they are under study for future applications. There is little doubt that by the time the space shuttle becomes a reality, these methods will have taken their place along with other standard methods.

ACOUSTIC EMISSION

When a metal is deformed, various internal processes result in the generation of elastic stress waves. At the microscopic level, the formation and movement of dislocations generates stress waves of low amplitude; at the macroscopic level, the propagation of cracks generates stress waves of much larger amplitude. Such stress waves consist of more or less sharply defined discrete pulses which propagate outward from their localized sources. Such a pulse is a superposition of sinusoidal components the individual frequencies of which cover a broad range from essentially zero Hz to many MHz. The process of generation and propagation of these stress waves has come to be called acoustic emission, despite the fact that in most practical cases only the ultrasonic components are detected. The prospect of "listening" to acoustic emission with appropriate instrumentation and thereby nondestructively characterizing a specimen is apparent. Although of great interest from a fundamental point of view, the detection of low-level acoustic emission associated with individual dislocation processes is at present useful only under controlled laboratory conditions. On the other hand, the detection of acoustic emission from a propagating macroscopic crack has proved to be practical. Instrumentation for this purpose, of varying degrees of sophistication and complexity, is now offered commercially by a few firms. In addition, some firms provide, on a contract basis, field service units of the most complex type.

Figure 1 is a block diagram of the usual components in a simple, single-channel acoustic emission monitor system. Sensors of various types are in use, virtually all of them based on piezoelectric materials. The differences among these are in natural frequency, bandwidth (produced by damping, at the expense of sensitivity), and vibratory mode (longitudinal or shear). It is important to recognize that the output signal from such a transducer is not in general a precise reproduction of the elastic stress wave impinging upon it. When affected by a stress wave packet of short duration, a high-Q (narrow bandwidth) detector is simply shocked into vibration at its natural frequency, and thereafter "rings down", the damping time being inversely related to Q. A damped, low Q detector, while less sensitive, produces an output which is

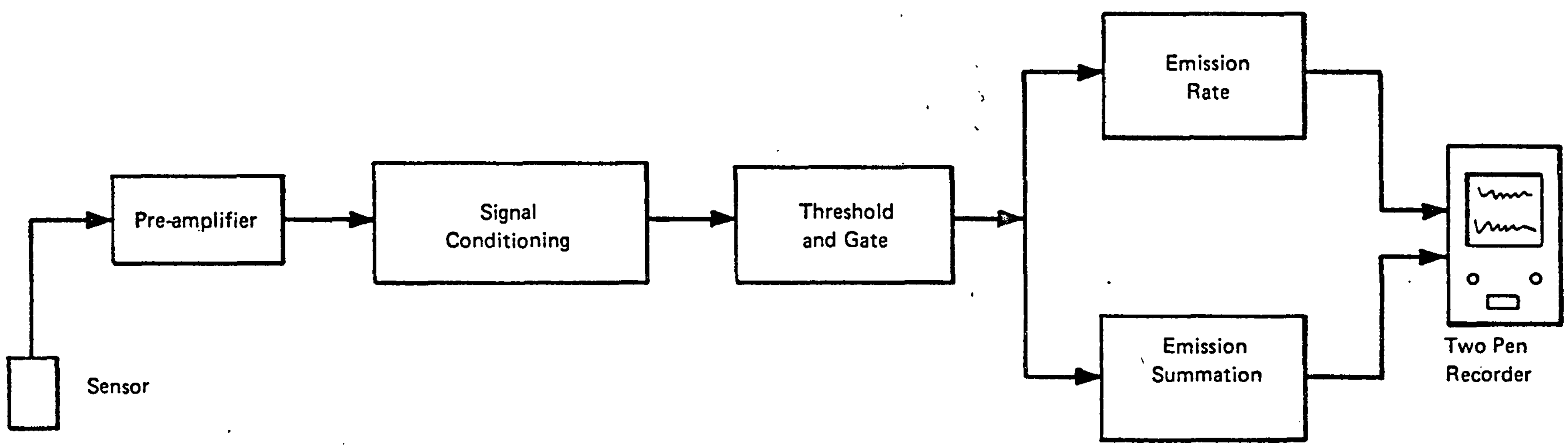

FIGURE 1. ELEMENTARY SINGLE-CHANNEL ACOUSTIC EMISSION MONITORING SYSTEM

a more precise analogue of the stress wave. Piezoelectric accelerometers have been used as acoustic emission detectors in the low to intermediate frequency range. The bandwidth and transfer function of the amplifiers and filters used also affect the signal finally observed. A high-gain, low-noise, wide-bandwidth preamplifier properly matched to the transducer is especially important if the spectral properties of the acoustic emission are of interest.

At present, most acoustic emission monitoring systems are based on the simplest possible signal processing, namely that of merely registering the arrival of a discrete stress wave packet. Systems differ in their ability to distinguish the arrival of a new packet from a variation in amplitude of a single packet of complex shape.

It has been experimentally demonstrated that the rate of emission of stress wave pulses, as detected by acoustic emission monitors, increases with the rate of growth of a macroscopic crack in a variety of materials. Hence, one application of acoustic emission monitoring is the surveillance of structures subject to possible catastrophic fracture. Prominent examples of the latter are pressure vessels and airframes.

Another application of acoustic emission monitoring is the location of propagating cracks by detecting a stress wave pulse with an array of two or more transducers. By measuring the differences in times of arrival of the stress wave at each of the transducers, the source may be located geometrically by triangulation. Rather elaborate systems employing many transducers and a digital computer programmed to perform the triangulation calculations on structures of considerable complexity (e.g., intersecting cylinders) have been developed. A block diagram of such a system is shown in Figure 2. Major applications to date have been on large storage tanks and on nuclear reactor pressure vessels during proof tests.

Further effort is being devoted to the development of better transducers, coupling methods, and signal analysis; to studying the effect of material properties and specimen geometry on the propagating stress wave; and to the correlation of rate of emission and other signal characteristics with flaw type, size, rate of propagation, etc.

NASA Contributions

NASA has, through a contractor, investigated the potential of acoustic emission monitoring for surveillance of rocket motor cases during proof pressure testing. The contractor concluded that the study illustrated the presence of a "critical stress-wave signature" the detection of which would indicate imminent failure in sufficient time to permit reduction of the pressure and thus prevent catastrophic destruction of defective motor cases (ref. 1).

In a further investigation by the same contractor, the correlation of stress-wave-emission characteristics with fracture in aluminum alloys was studied. Standard laboratory pre-cracked flat tensile specimens were used. Typical results obtained are shown in Figures 3 and 4. Figure 3 shows the cumulative stress-wave emission count and the test specimen crack length as functions of the applied tensile load for the representative single-edge-notch specimen of 2014-T651 aluminum. Figure 4 shows a graph of stress-wave-

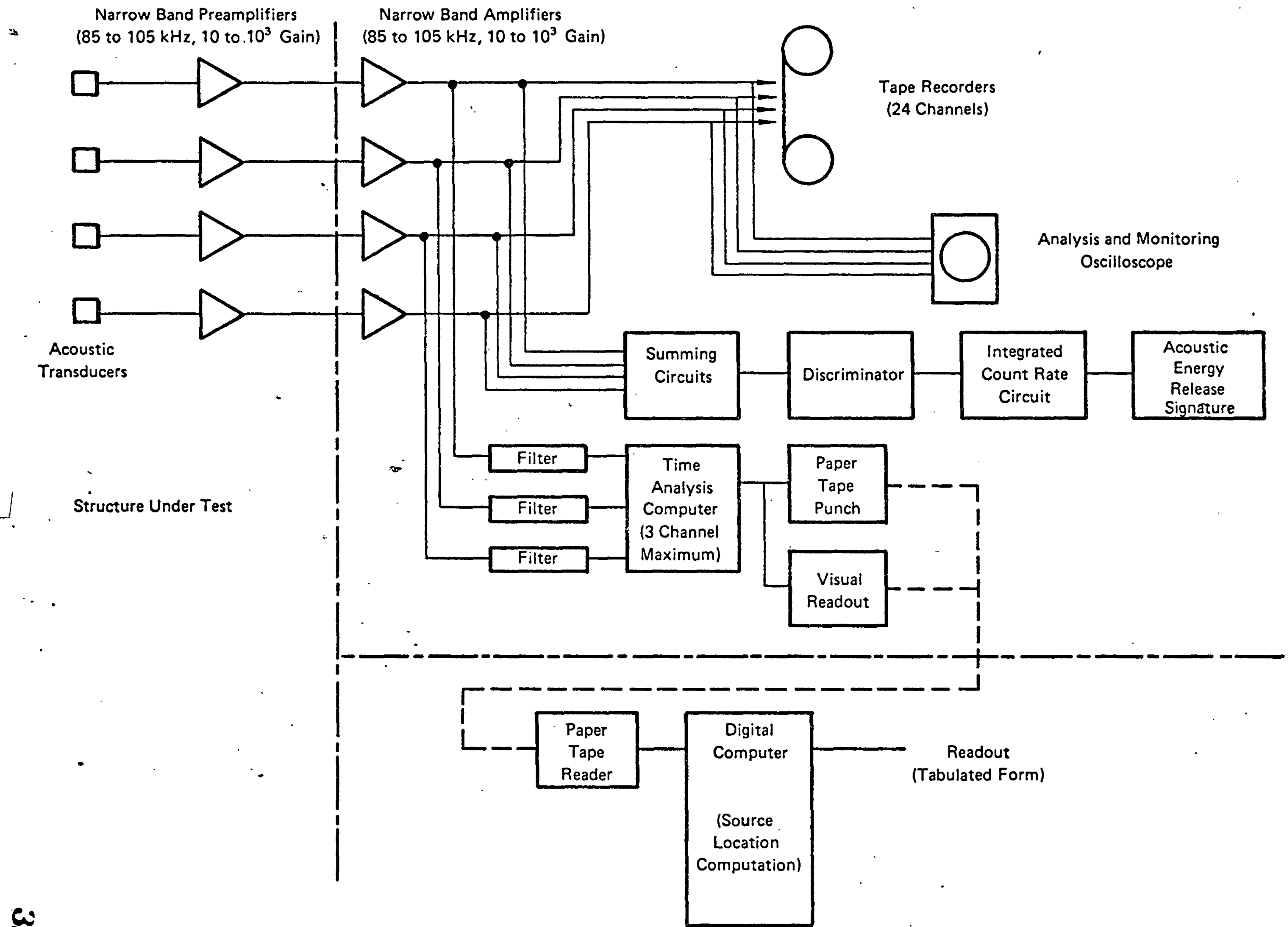

FIGURE 2. MULTICHANNEL ACOUSTIC EMISSION MONITORING AND FLAW LOCATION SYSTEM

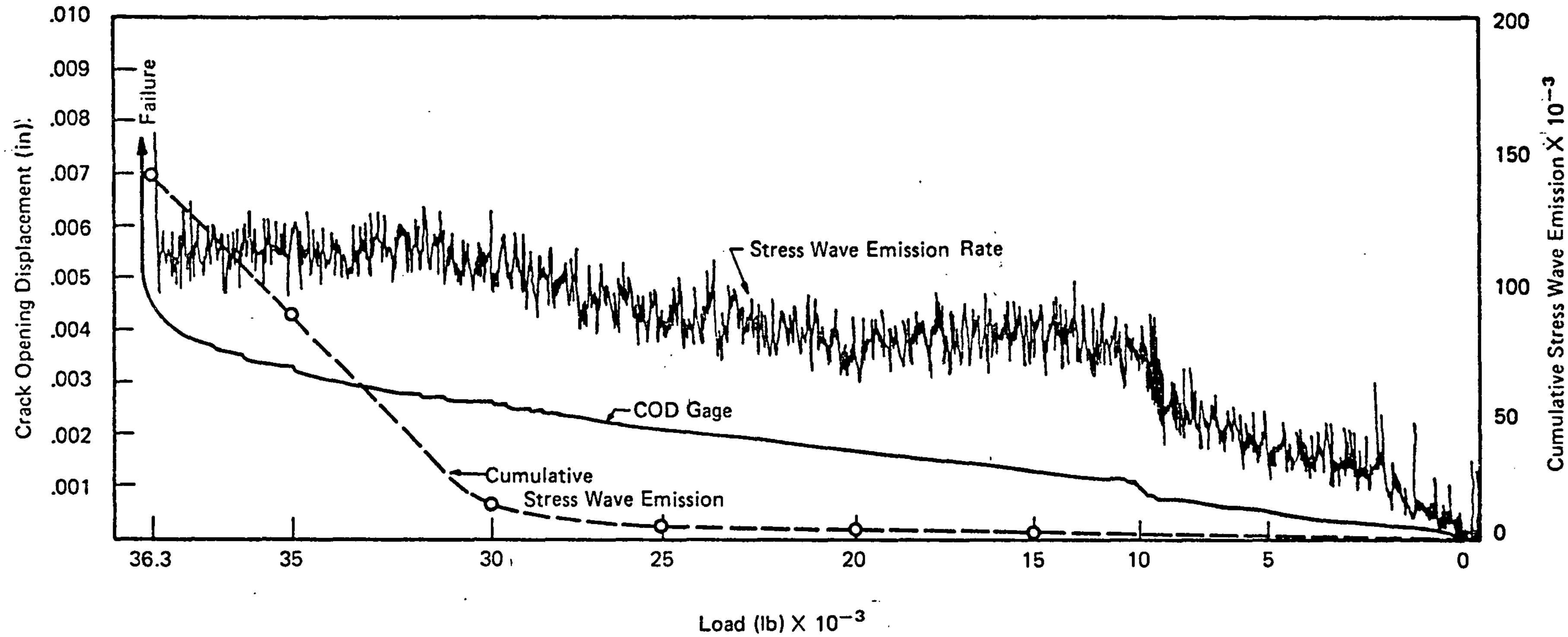

FIGURE 3. STRESS-WAVE EMISSION RATE AND CUMULATIVE COUNT, AND CRACK OPENING DISPLACEMENT (COD) FOR 2014-T651 ALUMINUM (ref. 1)

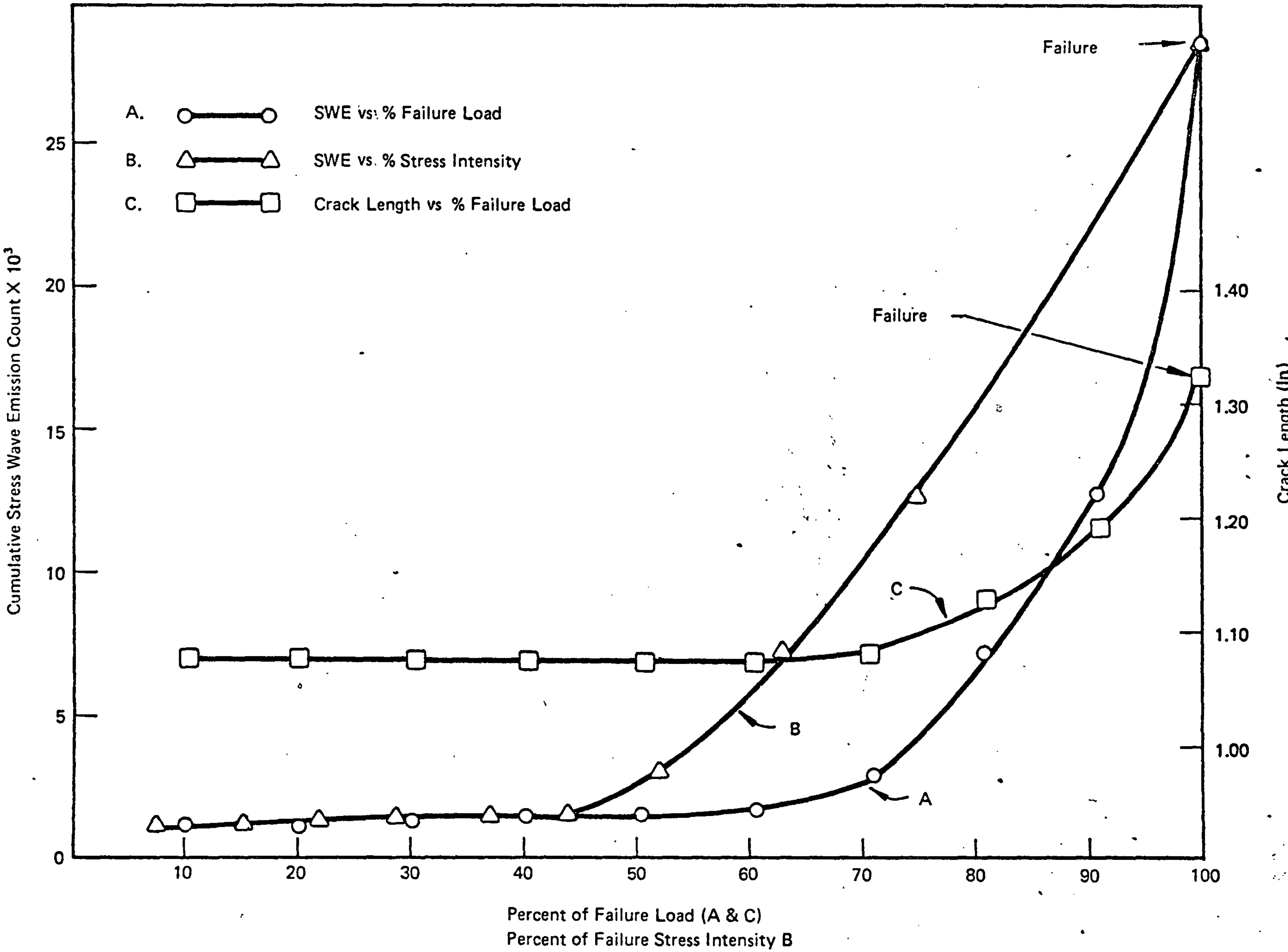

FIGURE 4. CUMULATIVE STRESS WAVE EMISSION COUNT AND CRACK LENGTH VS % FAILURE STRESS INTENSITY AND LOAD FOR 2014-T651 ALUMINUM (ref. 1)

emission rate, accumulated stress-wave-emission, and crack opening displacement, versus applied load, for a specimen of the same alloy having a part-through crack. From this and similar data, the contractor concluded that stress-wave-emission accompanying crack growth could be used as a precursor to the onset of a critical stress-intensity failure condition, although substantial differences in stress-wave-emission characteristics were found among different aluminum alloys tested (refs. 2 and 3).

COHERENT LIGHT METHODS

A number of related NDE methods based upon the coherence property of laser light are under development. The most important of these thus far are holographic interferometry and multi-frequency contouring. Optical correlation and laser speckle effects are still essentially confined to the laboratory. All of these methods are based upon the idea of sensing more or less subtle features of the surface of a test specimen. If a flaw or damage mechanism does not (or cannot nondestructively be made to) alter the shape of the surface of the specimen, coherent light methods are inapplicable (excluding the case of transparent materials). Holographic interferometry provides a means of comparing an object either with a holographically recorded image of itself, or with that of another closely similar object, thus making evident regions where the shapes differ. Multifrequency contouring provides a means of making a "relief map" of the surface of an object, with the capability of making evident very minute relief features. Optical correlation provides a means of comparing a surface with a holographic record of the same surface at a previous time, the comparison being on the microscopic scale of crystalline dislocation features; the method currently employed produces an electronic signal the amplitude of which is proportional to the degree of similarity (i.e., correlation). Speckle effects provide much the same sort of information as optical correlation but requires only an ordinary photograph of the laser-illuminated surface rather than a hologram of it.

Holographic Interferometry

A hologram is a photographic* recording of the interference pattern created in the photographic emulsion by two beams of light, one of which is reflected by a particular subject, and the other of which is a reference beam. The basic arrangements for recording and reconstructing a hologram is shown in Figure 5a and 5b. When the exposed photographic plate is developed the resultant image of the interference pattern is essentially a somewhat complicated transmission grating capable of diffracting a transmitted beam of light. If the hologram is illuminated by the original reference beam used in making it, that beam is diffracted in such a manner that the light diffracted on either side of the directly transmitted ("zero order") beam has wave fronts corresponding precisely to the wave fronts originally emanating from the subject. The eye

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* Media other than photographic emulsions are being explored, but are not in common use.

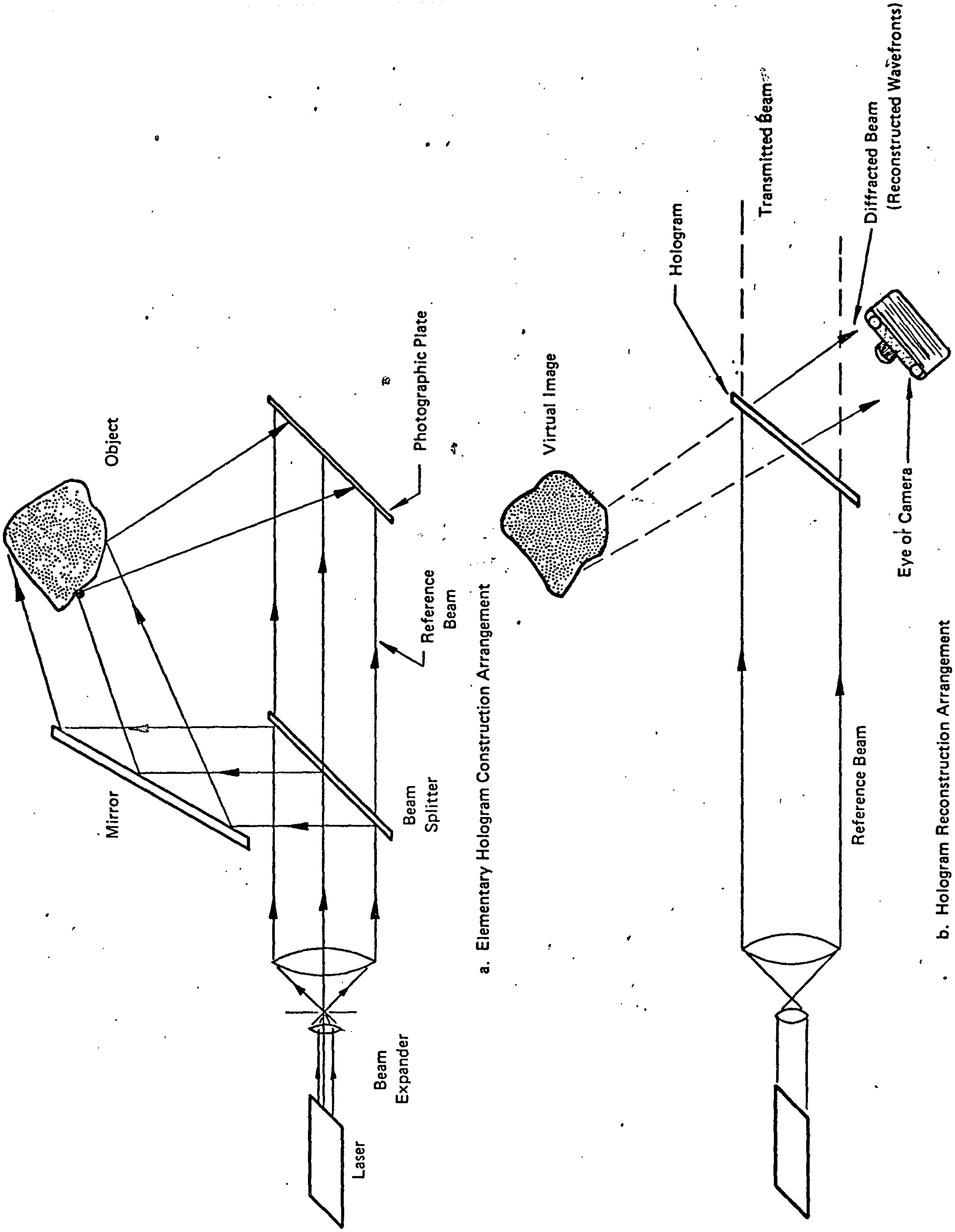


FIGURE 5. BASIC ARRANGEMENTS FOR RECORDING AND RECONSTRUCTING A HOLOGRAM

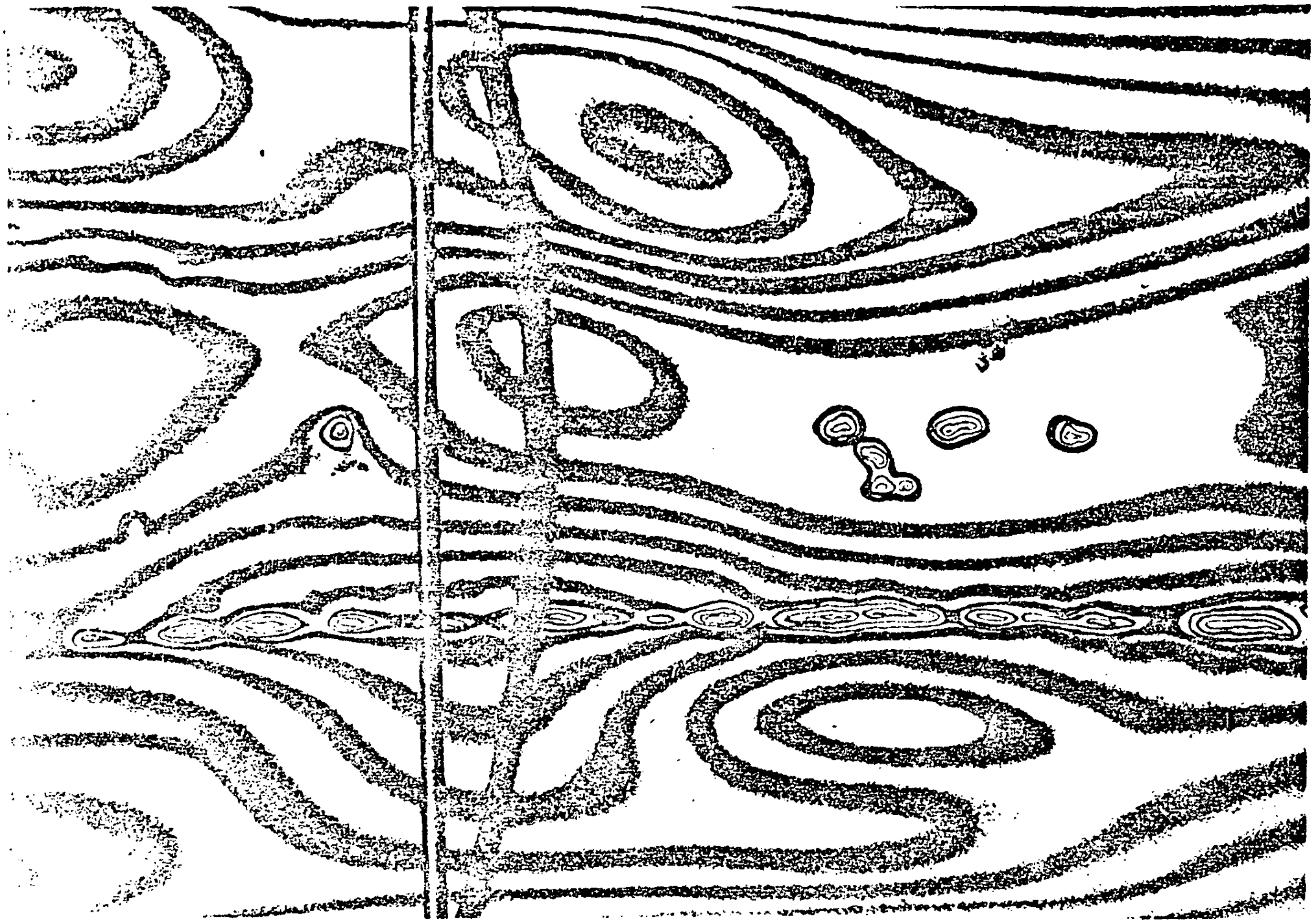
(or a lens) sees these reconstructed wave fronts as images of the original subject. One of the images is "virtual", i. e., it appears to be behind the hologram in the location of the original object; the other is "real" i. e., it appears in front of the hologram and can be displayed on a screen or viewed as a "space image". Only the virtual image is used in holographic interferometry. Since the holographically reconstructed wave fronts which produce the images have all the features of the wavefronts which originally emanated from the object, the images are truly three-dimensional; when viewed by the eye such an image has the appearance of depth and parallax.

Holographic interferometry is accomplished by replacing the developed hologram in its original position with respect to the object, the reference beam, and the illumination beam. Under conditions of precise repositioning, the virtual image of the object spatially overlaps the object itself, and, to the eye or camera, appears to merge with it, If, however, the object itself has changed dimensionally, a ray radiating from a point on the illuminated object, and passing through the hologram directly to the eye or camera, will in general differ in path length from that of the corresponding ray from the virtual image of the object. Because of this difference in path length, a corresponding phase difference exists, and an interference fringe pattern occurs. The observed fringe pattern can be analyzed to yield the deformation of the object with respect to its original form at the time its hologram was made.

As described above, the interference fringe pattern can be observed or photographed in real time; thus this method lends itself to the study of deformations induced by applied mechanical loads or by thermal stressing. An alternate method, called the double-exposure method, is to record on a photographic plate the hologram of the object in its reference condition, and subsequently record in the same (undeveloped) plate the hologram of the deformed object (being careful to preserve the arrangement of object, light beams, and photographic plate). When developed and illuminated with the reference beam (this time with the actual object removed), the reconstruction contains the superimposed images of the object in the two conditions to be compared, and an interference fringe pattern is also constructed.

Figure 6a is a photograph of a real-time holographic interferogram of a portion of the inner surface of an automobile tire. The larger contours are not indicative of flaws; however, the chain of small, fine contours is indicative of localized ply separations. Figure 6b is a photograph of a section through the same tire showing the actual ply separations nondestructively indicated in Figure 6a.

Real-time holographic interferometry is being applied, on an experimental basis, to the detection of flaws in pneumatic tires, disbonded regions in honeycomb composite structures, and the like. It is also being investigated as an approach to compare the shape of production line items of precision shape with a holographically recorded "master template".



a. Holographic interferogram of portion of tire interior

b. Section through same tire revealing ply separations associated with features of the interferogram

FIGURE 6. TIRE FLAWS DETECTED BY HOLOGRAPHIC INTERFEROMETRY
(Courtesy GCO, Inc.)

Holographic Vibration Analysis

If a time-exposure hologram is made of an object undergoing cyclic vibration, the resultant time-averaged hologram, when reconstructed, shows a time-averaged fringe pattern which defines the vibrational modes of the surface and their nodal regions. This holographic approach to vibrational analysis can also be used to detect flaws which produce vibrational anomalies. The method is, however, not a real-time method; it requires development and reconstruction of the time-averaged hologram.

An alternative, real-time approach to holographic vibrational analysis is to prepare a reference hologram of the object at rest, set up the system for conventional real-time interferometry, set the object to vibrating, and then stroboscopically observe the dynamic interference fringe pattern.

Holographic Contouring

If simply a "relief map" of a surface is desired, holographic differential interferometry need not be resorted to; more direct methods have been developed. One method is the dual-source method in which a hologram of an object is prepared using two mutually coherent point sources of laser light as the illumination beam. The interference pattern of the two sources, formed on the surface of the object, appears in the reconstructed holographic image as contours defining the relief features of the surface. An alternative, and generally superior, approach is to use an illumination beam and a reference beam each made up of two wavelengths rather than one. Several lasers are available which provide such beams. When the resulting hologram is illuminated by a single-frequency laser beam, two images with slightly different positions are produced. These two images interfere, and (for appropriate geometries) the resulting image contours are accurate indications of surface relief. Figure 7 shows a two-frequency contour map of the surface of a coin. The two wavelengths used were 6328Å and 6118Å. Each fringe interval represents a depth difference of 9.25 μm.

Holographic contouring has not thus far found as many promising applications as an NDE method as has holographic interferometry. One laboratory application is in the study of surface strains associated with fatigue damage. It may also find application in evaluating the perfection of precision parts such as roller bearing components.

Optical Correlation

With the real-time holographic interference arrangement, if, instead of using a final imaging arrangement to make a photograph of the object and its superposed, holographically produced, virtual image, the light passing through the hologram is brought to a focus by a single lens, the intensity of light at the focal spot is proportional to the degree of correlation of the real object and its virtual image. Thus a photometer located at the focus of the lens can, in effect, produce a signal proportional to the degree of correlation. It has been demonstrated that by this method fatigue-induced changes in the surface microstructure of a fatigue specimen can be detected and measured prior to the onset of visible cracking. The method has thus far not progressed beyond the laboratory demonstration stage.

FIGURE 7. TWO-FREQUENCY HOLOGRAPHIC CONTOUR MAP
(Courtesy of Prof. J. R. Varner, University of Michigan)

NASA Activities

NASA-sponsored work in holographic instrumentation applications through 1969 has been reviewed elsewhere (ref. 4). Only some highlights of potential importance in NDE will be mentioned here.

The visualization of fluid flow fields by holographic techniques has been investigated both at NASA Centers and by NASA contractors. The potential advantage would appear to be in very low pressure gases, characteristic of the upper atmosphere. Holographic vibrational analysis is also being studied for application to aerospace structures. An investigation of considerable interest for NDE is the use of coherent light to create visual images from microwave holograms. All these investigations are presently in exploratory or early development phases.

ULTRASONIC HOLOGRAPHY

Optical holography was made possible by the development of practical sources of coherent light. Sound, like light, is a wave phenomenon, though of an entirely different kind; furthermore, sources of coherent sound have been available for centuries. Yet, strangely, no one appears to have thought of making "sound holograms" until after optical holography was developed. Although sound holograms could in principle be made using sound of any frequency, from the point of view of NDE, ultrasonic frequencies are most useful; hence the term "ultrasonic holography" is preferred over the term "acoustical holography" which is sometimes used.

An ultrasonic hologram is made in a manner similar to that in which an optical hologram is made; ultrasonic waves simply take the place of light waves in the illumination beam and reference beam. Of course, photographic film cannot be used directly to record the resulting interference pattern. While various schemes have been proposed for recording ultrasonic holograms, thus far the only one to meet with any significant degree of success is the so-called ripple tank. The hologram is produced by action of the interfering ultrasound beams impinging upon the water surface to produce a steady-state ripple pattern, the hologram. This may be photographed (under appropriate illumination) to give a permanent hologram from which the image can be reconstructed and made visible by illumination with a visible-light laser beam. This method of reconstruction is somewhat impractical because the reconstructed image is smaller in lateral dimensions than the original scene by the ratio of the wavelength of the light used to the wavelength of ultrasound used, a very small fraction. A more practical method, which also has the advantage of being a real-time method, is to illuminate the ripple pattern with a coherent light beam and view the hologram by reflection, as shown in Figure 8. The demagnification effect still takes place; however, this may be overcome by viewing the reconstructed scene through appropriate magnifying optics. A closed-circuit television system may also be used to view the image. A system incorporating these features is now offered by a commercial manufacturer.

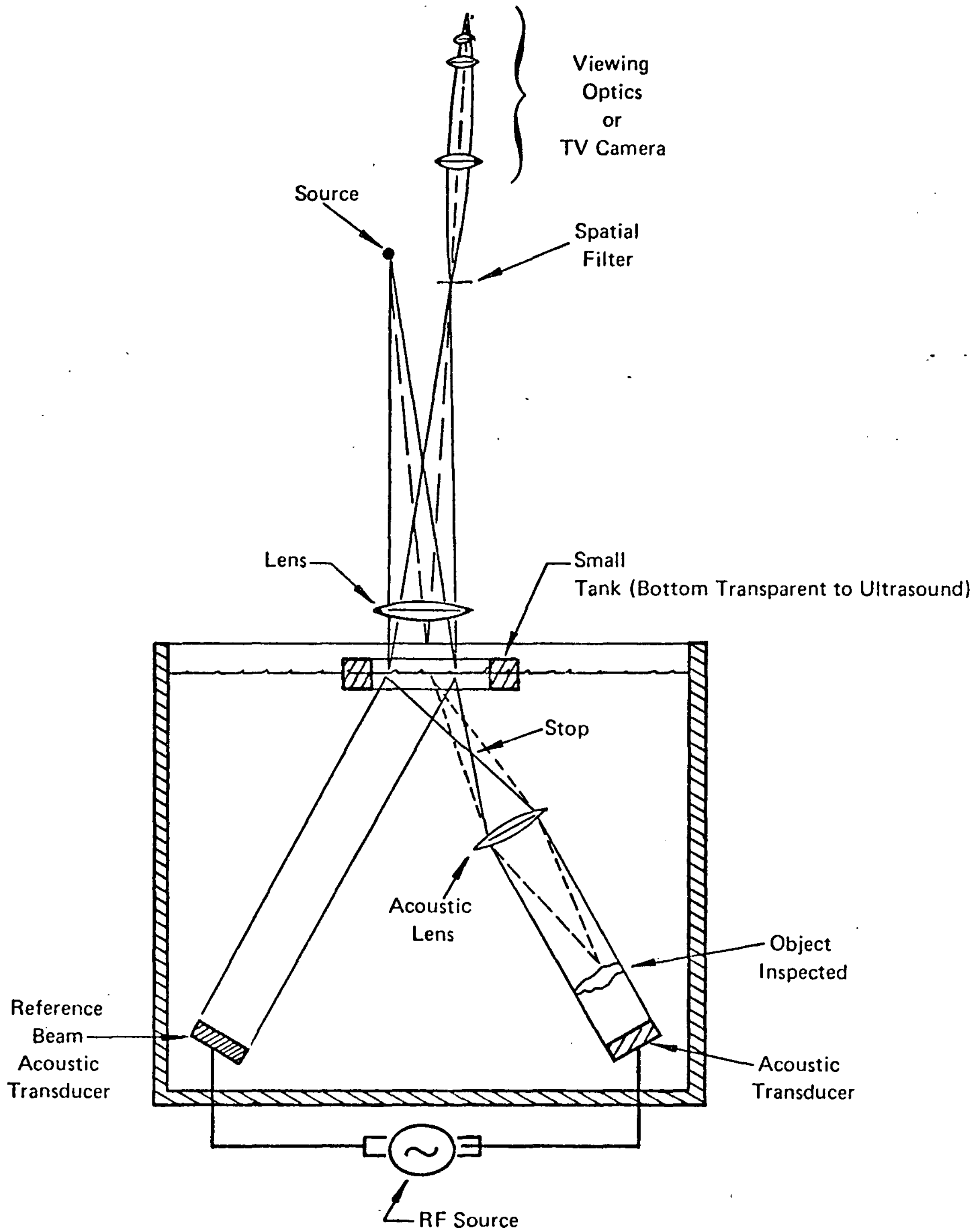


FIGURE 8. SCHEMATIC DIAGRAM OF RIPPLE TANK ARRANGEMENT FOR REAL-TIME ULTRASONIC HOLOGRAPHY

Ultrasonic holography has the advantage of presenting a visual image of what the ultrasound "sees" in the bulk of an inspected object, a feature which can be a great help. However, the method also has disadvantages. First, the resolving power of the system is intrinsically limited by the wavelength of the ultrasound used. Secondly, it is difficult to apply the method to objects of irregular shape; mode conversion at the interface of the water and the inspected object and multiple internal reflections and scattering create problems. Thirdly, the size of object that can be inspected is limited by the size of water tank available and by attenuation in the inspected object. These disadvantages are subject to amelioration through further research and development, and it appears likely that ultrasonic holography will in the future find wide application in NDE.

An alternative, essentially nonholographic, method of using ultrasound and laser light to create a visual image of the interior of an object has also been developed. This method, which depends upon Bragg diffraction of light by the sound beam, is still in the research stage; commercial versions have not been developed (ref. 5).

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